Methodology Development

Screening Life Cycle Impact Assessment with Weighting Methodology Based on Simplified Damage Functions

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Abstract. The procedure of screening LCIA with weighting methodology and the result of a case study have been described. The weighting methodology incorporates the impacts related with input and output by the simplified damage functions. Through the dominant analysis by this methodology, we can detect the significant substances and environmental problems in life cycle of the product. With this result, LCA practitioners can concentrate on the analysis for these items to improve the reliability of investigation effectively in the following step. According to the result of case study, an imaginary copy machine, the primary consideration in the foreseeable study should put emphasis on the analysis of the consumption of natural gas and wood, and the emission of carbon dioxide.

Keywords: Carbon dioxide; case study; damage functions; LCA practitioners; LCIA; life cycle impact assessment; natural gas; screening LCIA; simplified damage functions; weighting methodology; wood

Introduction

According to ISO 14042 (2000), weighting is the process of converting indicator results of different impact categories by using numerical factors based on value-choices. To maintain the reliability of the result of LCA, assessment should only be based on natural science. Consequently, although weighting is one of the elements of the LCIA phase, this step is treated as an optional element and cannot be used in comparative assertions disclosed to the public in LCIA.

In Japan, however, the requirement of development of weighting methodology is very stringent. LCA practitioners or product designers are not always environmental scientists. It may be very difficult for them to make a decision with only an inventory table or category indicators, if quantified substances and impact categories meet complicated tradeoff relationships in comparison to several product systems. Furthermore, they may have to get an answer as soon as possible to reduce the cost in an LCA study. It is necessary to consider that the result should be facilitated to interpret for decision-makers. Consequently, it is important to provide the screening approach by dominant analysis to shorten the time for investigation. Actual weighting contains value-choices, although we can detect what are important substances effectively through the weighting. As a screening LCIA, we developed I-O integration. The authors have applied this method for 1800 types of Japanese products to consider the interactions between industrial products manufactured in Japan and current Japanese environmental problems (Itsubo, 1997; 1998a; 1999).

In this paper, we described the procedure of screening LCIA by I-O integration and a result of a case study.

1 Methodology Overview

1.1 Basic view point of I-O integration

Conceptual figure of the I-O integration methodology proposed is shown in **Fig. 1**. This method considers 11 types of impact categories (ozone-layer depletion, photochemical oxidant creation, air pollution, water pollution, greenhouse effects, carcinogenic substances, acidification, eutrophication, depletion of energy resources, depletion of mineral resources, depletion of biotic resources) and three types of safeguard subjects (human health, ecological health, resources). The affected endpoints are dependent on impact categories. This method assumed that the effects of greenhouse effects and carcinogenic substances are assigned into several safeguard subjects, human health and ecological health, because these categories affect many types of endpoints comparatively. This procedure is similar with the assignment of the emission of inventory (ex. SO_x) into several impact categories (ex. acidification and air pollution) in classification, one of the phases of LCIA. The other effects, such as the ecological effects by ozone layer depletions and photochemical ozone creations, were neglected to simplify the method. We regarded water pollution and air pollution as impact categories. The substances that have a political environmental standard for air (for example sulfur dioxide, carbon oxide) and water (for example cadmium, lead) in Japan can be classified into these categories. These categories are supposed to have an interaction with human health, because environmental standards for these substances have been determined to avoid a health effect.

This method contains two types of weighting, weighting across impact categories to aggregate into a safeguard subject and weighting across safeguard subjects to obtain a single index. Weighting factors applied in this method are described in section 1.3. Through this methodology, we can obtain four types of calculated results, aggregated single index, the potential damages to safeguard subjects, category

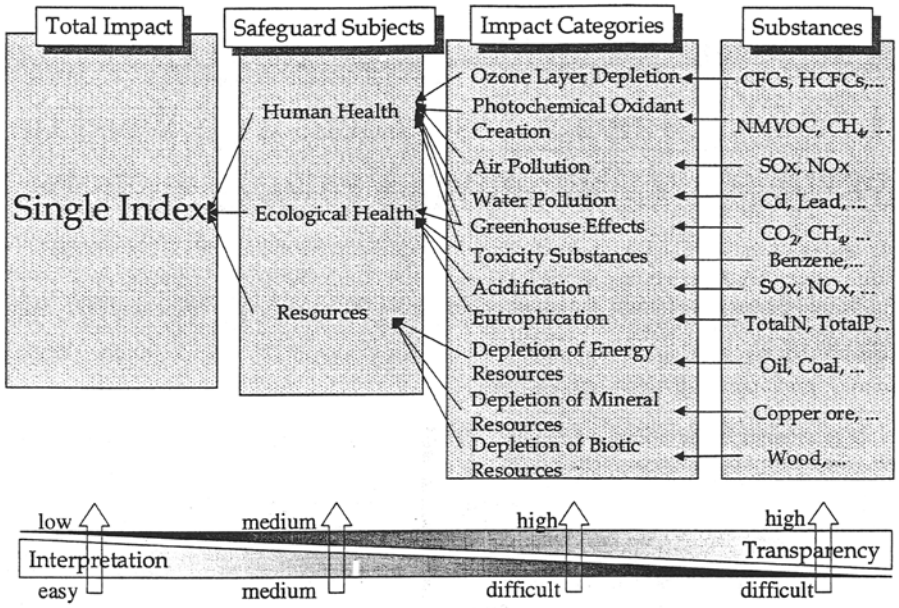

Fig. 1: Conceptual figure of I-O methodology: Four types of calculated results differ the degree of transparency and facility to interpret

indicators obtained by characterization and an inventory table. These types of result differ in the numbers of quantified subjects and the reliability of result. These differences will lead to the following distinction. Aggregated single index involves value-choices between safeguard subjects like human health and resources. This value-choice is completely dependent on the LCA practitioner, the deviation of the result of weighting would be larger than the previous results such as an inventory table and a category indicator. However, an LCA practitioner can obtain just one quantified result by weighting. It is very easy to perform a decision making process without any trade-off relationship under the condition that LCA practitioners understand the concept of impact assessment. On the other hand, the reliability of a result by an inventory table and category indicators is higher, because they can keep away from subjectivity. It might be difficult, however, to interpret the results of former steps, because the possibilities of an occurrence of the trade-off relationships between the quantified results are higher than that of the latter steps like weighting. Potential damage of safeguard subjects would be middle level in both aspects. An LCA practitioner can choose the suitable type of result with considering the aim of study and the characteristics of the results.

1.2 How to estimate the total impact

Impact categories considered in LCIA can be divided into two categories roughly, impacts related to output like greenhouse effects and impacts related to input like abiotic resources according to Udo de Haes et al. (1996). We established the simplified damage functions that estimate environmental impacts related with input and output, respectively.

The damage function that expresses the relationship between the potential damage of resource (safeguard subject) and consumption of limited resources (inventory data) is shown in **Fig. 2**.

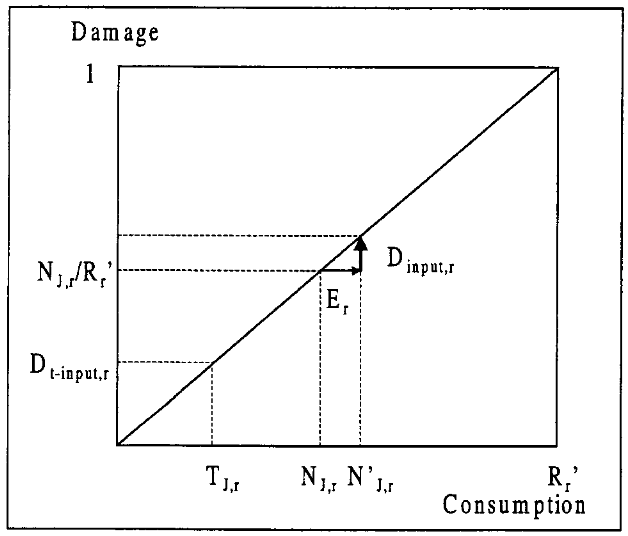

Fig. 2: Simplified damage function for input-related impact category

We assumed that the shape of the damage function is linear and go through the origin for simplicity. If we mine the ore, the reserve of the resource will be reduced. This reduction of reserve is regarded as the potential damage of resources, and then the simplified damage function of the input can be expressed as eq. (1).

$$
\begin{aligned}
D_{input} &= \sum_r D_{t-input,r} \times \frac{E_r}{T_{J,r}} = \sum_r D_{t-input,r} \times \frac{E_r}{\left(\frac{R'_r}{100}\right)} \\
&= \sum_r D_{t-input,r} \times \frac{E_r}{\left(\frac{R_r}{100} \times \frac{N_{J,r}}{N_{G,r}}\right)} = \sum_r D_{t-input,r} \times \frac{E_r}{N_{J,r}} \times \frac{N_{G,r}}{\left(\frac{R_r}{100}\right)}
\end{aligned}
\quad (1)
$$

D_{input}: Damage of safeguard subject 'consumption of resources' (all resources)
$D_{t\text{-}input,r}$: Damage of resource r in case the present environmental impacts are equal to target value
E_r: Consumption of resource r through the life cycle of product.
$T_{J,r}$: The target value of the consumption of resource r in Japan
$N_{J,r}$: Annual consumption of resource r in Japan
$N_{G,r}$: Annual consumption of resource r in world
R'_r: The amount of resource r is supposed to be able to consume in Japan
R_r: Confirmed reserve of resource r

We temporarily established a target value for resources so that we can consume 100 years with the current consumption rate. If we assess the recycled steel that is not required for mining iron ore, this means there is no damage concerning the reserve of iron ore. However, electricity will be consumed for the production of secondary steel and the damage of energy resources like oil and coal have to be counted.

Fig. 3 shows the damage function concerning output categories in a simplified form. The relationship between the effects of the impact category and the potential damage is also supposed to be linear and go through the origin.

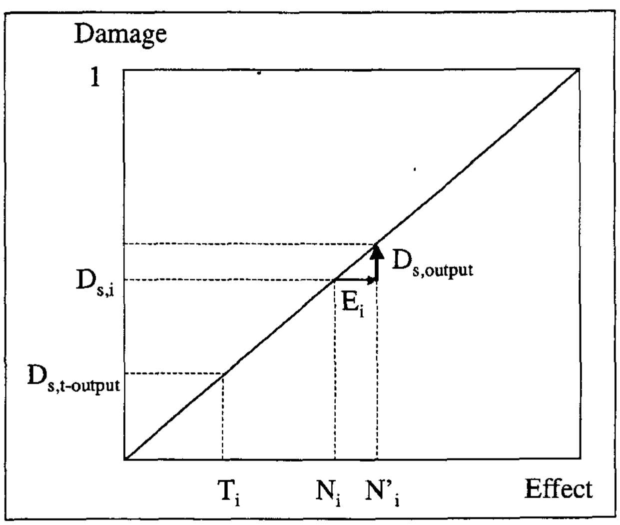

Fig. 3: Simplified damage function for output-related impact category

From Fig. 3, the environmental impact or damage caused by a product or material can be expressed as follows:

$$D_{output} = \sum_s D_{s-output} = \sum_s D_{s,t-output} \times \frac{E_i}{T_i} = \sum_s D_{s,t-output} \times \left(\frac{E_i}{N_i} \times \frac{N_i}{T_i} \right) \quad (2)$$

D_{output}: Aggregated damage of safeguard subjects by the emission of environmental loading substance
$D_{s\text{-}output}$: Damage of each safeguard subject by the emission of substances
$D_{s,t\text{-}output}$: Damage of each safeguard subject in case the present environmental impacts are equal to the target value

E_i: Incremental effects of impact category i caused by product life cycle
N_i: Normalization value of impact category i
T_i: Target value of impact category i

In case the LCA practitioner's goal of impact assessment is to obtain the total single index, we must aggregate the impacts related with input and output. The aggregation of environmental impacts can be expressed as following by the utilization of the factor that indicates the priority between safeguard subjects.

$$I = \sum_s W_s D_s = W_h D_h + W_e D_e + W_r D_r$$
$$= \sum_s \left(W_{output} D_{s,t-output} \sum_i \left(\frac{E_i}{N_i} \times \frac{N_i}{T_i} \times R_i \right) \right) + W_{input} D_{r-input} \sum_r \left(\frac{E_r}{N_{J,r}} \times \frac{N_{G,r}}{R_r/100} \right) \quad (3)$$
$$= \sum_s \left(W_{output} D_{s,t-output} \sum_i \left(\frac{E_i}{N_i} \times W_i \times R_i \right) \right) + W_{input} D_{s-input} \sum_r \left(\frac{E_r}{N_{J,r}} \times \frac{100}{Y_r} \right)$$

I : Single index
W_s : Weighting factor of safeguard subject (h: human health, e: ecological health, r: resources, output: safeguard subjects related with output, input: safeguard subjects related with input)
D_s : Potential damage of safeguard subject (h: human health, e: ecological health, r: resources)
W_i : Weighting factor of impact category i
R_i : Ratio of damaged area
Y_r : The life of resource r

The single index calculated by this equation means the total of the potential damages of safeguard subjects. The first term on the right side indicates the environmental impact by the emission of substances (output). The second term estimates the impact by the consumption of resource (input). This methodology considers three items of the safeguard subjects (human health, ecosystem, and resources). The former two subjects are related with output categories like greenhouse effects, acidification, while the latter is concerned with the input category like resource depletion. Eq. (3) incorporates the ratio of damaged area to consider the difference of the geographical range between impact categories. We described the concept and procedure for the estimation of factors applied in this method in the next section.

1.3 Factors in I-O integration

Normalization values can be obtained by multiplying the annual emission of substances in Japan with characterization factors. Annual emissions of environmental loading substances and annual consumption of limited resources have been investigated in JEMAI (1999). Normalization values in this method based on this investigation are summarized in **Table 1**.

Halada et al. (2000) carried out a panel test whose methodology and procedure has been originally developed by UNS-ETH for Japanese LCA experts aimed at the weighting of three safeguard subjects in the panel approach. The questionnaire was sent out to 438 members of JLCA, and 111 questionnaires (26%) were returned. According to this re-

Table 1: The list of normalization value and considering substances to estimate

	Normalization Value (Characterization Factor*ton)	Characterization Factor	Substances considered in normalization
Greenhouse Effects	**1,29E+09**	GWP_{100}	CO_2, CH_4, N_2O, HFC134a, HFC23, PFC-14, PFC-116, SF_6, HCFC141b, HFC142b-1
Ozonelayer Depletion	**4,66E+03**	ODP	HCFC141b, HCFC142b, CH_3Br, CCl_4, 111TCE
Acidification	**5,17E+06**	AP	NOx, SO_2, NH_3, HF, HCl
Photochemical Oxidant Creation	**7,90E+05**	POCP	CH_4, NMVOC
Nutrification	**2,36E+05**	NP	Total-N, Total-P, BOD
Air Pollution	**4,47E+06**	HCA	SOx, NOx
Water Pollution	**1,08E+05**	HCW	Cadmium, Cyanide, Lead, Chromium, Arsenic, Mercury, PCB, Dichloromethane, Tetrachloromethane, 1,2-dichloroloethane, 1,1-dichloroethylene, sis-1,2-dichloroethylene, 1,1,1-TCE, 1,1,2-TCE, Trichroloethylene, Tetrachloroethylene, 1,3-dichloropropene, Titanium
Carcinogenic Substances	**3,96E+05**	HCA	Acrylonitrile, Acetoaldehyde, Vinyl Chloride, Chloroform, 1,2-dichloroethane, dichloromethane, Dioxins, Tetrachloroethylene, Trichloroethylene, 1,3-Butadiene, Benzene, Benzo(a)pyrene, Formaldehyde

sult, the relative importance of the safeguard subjects was human health: ecological health: resources: 40:40:20. We adopted this result, and established the weighting factors for human health, ecological health, and resources as 0.4, 0.4, and 0.2, respectively.

Weighting factors across the impact categories can be obtained by the comparison between the target value and the present value in Japan. This approach belongs to the Distance to Target method that is represented in the Eco-scarcity method (BUWAL, 1997) and Eco-indicator 95 method by Goedkoop (1995). It is important to establish the weighting factors considering the area, because the target value and the present situation are dependent on the area of emission considered for the calculation. **Table 2** shows the present situations of water areas in Japan and the procedure to estimate the weighting factor and ratio of the damaged area for eutrophication, for instance.

First of all, we surveyed the present concentration of nitrogen and phosphorus in the closed water area of Japan such as lakes and marsh from the previous research (Environ-

Table 2: Procedure for determination of weighting factor and ratio of damage area for eutrophication in Japan

Water area	Total-N	Total-P	Present Value	Target value	Present value/Target value	Damaged or No damaged	Area
Name	mg/l	mg/l	NP * concentration	NP * environmental standard	dimensionless	Yes or No	km2
Abashiri-Lake	0,92	0,060	0,570	0,405	1,407	No	32,3
Shikotsu-Lake	0,10	0,003	0,051	0,195	0,262	No	78,4
Touya-Lake	0,21	0,006	0,107	0,195	0,546	No	70,7
Ohnuma	0,52	0,021	0,283	0,260	1,088	Yes	5,3
Akan-Lake	0,28	0,026	0,197	0,260	0,759	No	13
Kussyaro-Lake	0,16	0,007	0,089	0,195	0,454	No	79,3
Inba-Lake	3,40	0,160	1,918	0,260	7,381	Yes	8,87
Tega-Numa	6,70	0,580	4,589	0,726	6,321	Yes	4,12
Biwa-Lake	0,52	0,029	0,307	0,115	2,680	Yes	670
Shinji-Lake	0,55	0,056	0,402	0,260	1,549	Yes	79,1
Ikeda-Lake	0,24	0,026	0,180	0,115	1,574	Yes	10,9
Unagi-Pond	0,19	0,008	0,104	0,115	0,910	No	1,2
Total 49 water areas							**1524**

mental Agency, 1999). Present values can be obtained by the sum of multiplication between the concentration of water area and Nutriphication Potential proposed by Heijungs et al. (1992). In Japan, the concentration of nitrogen and phosphorus have been regulated in establishing the environmental criteria for each closed water area with the classification into the several types. We can get the target values for each water area by multiplication of the environmental standard of nutrient and Nutriphication Potential. Next, the present values have been divided by the respective target values of the closed water area. The maximum of these ratios, worst case, is assumed as a weighting factor for the eutrophication in this method.

If we apply this weighting factor directly in the present situations in Japan, all of the water area in Japan might be treated as serious as the water area of worst case. The geographical area of the damage is dependent on the impact category; greenhouse effects global effects, eutrophication can be considered as a local impact. Weighting factors for global and regional effects except for local impact categories were obtained by the averaged target value and present value in Japan. Consequently, there is the possibility that the environmental impact for local level may be overestimated as compared with an impact category that has a global effect. We introduced the ratio of the damaged area that estimates the rate of area occurring the damage actually to revise this overestimation for the assessment of a local impact category. In case that the present value is larger than the target value in a certain area, this area is actually supposed to have the damage. In the other case, where the present value is lower than that of the target, we assumed that there is no damage in that area. We calculated the ratio of damaged area by the counting the area in km² of damaged water area and divided it by the total closed water area in Japan. The ratio of damaged area can be obtained in the following equation:

$$\textit{Ratio of Damaged Area} = \frac{\textit{Sum of Exceeded Area}}{\textit{Sum of Assessed Area}} \tag{4}$$

With this equation, the ratio of the damaged area for eutrophication can be estimated as 0.80. The same procedure has also been applied for the other local impact categories such as air pollution, water pollution, toxic substances, and photochemical oxidant creation. Through these analyses, we estimated for the factors to perform the weighting. The weighting factors of impact categories and ratio of damaged area are listed in Table 3.

Table 3: The list of weighting factor and the ratio of damaged area of impact category

Impact Category	Geographical Scale	Weighting Factor	Criteria for weighting factors of impactcategories	Ratio of Damaged Area	Protection Area Related with Impact Category		
					Human Health	Ecological Health	Resources
Greenhouse Effects	Global	2,24	Tg = Ng(1990)×0.4 The target value; The annual emission of all greenhouse effect gas must be reduced 60% of 1990s (Japanese EPA).	-	O	O	-
Ozonelayer Depletion	Global	1,53	The target value; the concentration of CFCs in 1979 (the previous of discovering ozone hall) The present value; the concentration of CFCs in 1992	-	O		-
Acidification	Regional	1	The present impact is equal or less than the value that produce no detectable effects	-	-	O	-
Carcinogenic Substances	Local	3,56	The target value; Sum of multiplying the amount of unit risk(10^{-6}) with characterization factors, The present value; Worst case of Japan	1	O	O	-
Human toxicity (water)	Local	1,84	The target value; Sum of multiplying environmental standard of Japan with characterization factor, The present value; Worst case of Japan	0,35	O	-	-
Human toxicity (air)	Local	1,95	The target value; Sum of multiplying environmental standards of Japan with characterization factors, The present value; Worst case of Japan	0,85	O	-	-
Eutrophication	Local	7,38	The target value; Environmental standard of Japan (N:1.0mg/l, P0.09mg/l), The present value; Worst case of Japan (N:14mg/l, P:1.2mg/l)	0,8	-	O	-
Photochemical Oxidants Formation	Local	3,57	The target value: Cocentration of ozone in Japanese environmental standard, The present value: Worst case of Japan	1	O	-	-
Resource Depletion	Global	-	Target value: The amount that is abailable for 100 years, The present value: Current annual consumption	-	-	-	O

2 Case Study

In this section, we present a case study in which this methodology has been applied. The inventory data used in this calculation is provided by the result of Japan/Europe international joint project. This project was carried out to clarify the difference of LCA approaches by the following European and Japanese organizations through the case study for the same product.

- Product Engineering GmbH (PE), IKP-University of Stuttgart, Germany.
- Swiss Federal Laboratories for Materials Testing and Research (EMPA), Switzerland.
- Centre of Environmental Science (CML), Leiden University, Netherlands
- Pré Consultants B.V., Netherlands
- National Institute for Resources and Environment, Tsukuba, Japan
- Japan Environmental Management Association for Industry, Tokyo, Japan

They assessed the imaginary copy machine with their original approach and compared their methodologies based on the calculated results. The intended application of this study is to create an information and knowledge basis for LCA activities. It will be exemplary conducted on a technical product. The functional unit equals one black & white copier machine as a standard application with no specific extra equipment or functionality. The modeled life cycle stages of the system include the demand of materials and energy for the manufacturing of the product, the manufacturing processes of the sub-assemblies and components, the final assembly of the product, the use phase and finally the end of life phase without recycling aspects, whereas the product is landfilled. Landfill emissions were neglected.

PE/IKP, EMPA analyzed an inventory, and CML, Pré Consultants were in charge of impact assessment (CML, 1999) (Pré, 1999). NIRE and JEMAI prepared preliminary data for inventory data such as weight of products and parts, usage periods, transportation scenario and etceteras. In this paper as a case study, we applied both the inventory data by (IKP/PE, 1999) and (EMPA 1999) into our methodology and compared these results to conduct a dominant analysis.

Calculated results have been introduced as followings. **Fig. 4** shows the environmental impacts divided into life cycle stages. A glance at Fig. 4 will reveal that usage stages are dominant in life cycle of an imaginary copy machine. The stages that manufacturing and assembly account for 25% of the total life cycle stages. The end of life of product was negligible. As shown above, the emissions after landfill were neglected. The result might be change, if we can include these stages. This figure also shows that consumption of energy and biotic resources in a use phase and the consumption of mineral resources in manufacturing phase are serious. The impact by greenhouse effects, eutrophication, photochemical oxidant formation in the use phase and the emission of toxic substances in the use and manufacturing phase are important.

Fig. 5 shows that the results of weighting are classified respectively into the damages of safeguard subjects. This result can be obtained by the assumption that the weighting factor of safeguard subjects is 0.4:0.4:0.2 as described above. We see from Fig. 5 that the damage of resources is more serious than the other two safeguard subjects. The damage due to depletion of biotic resources is caused by use of pa-

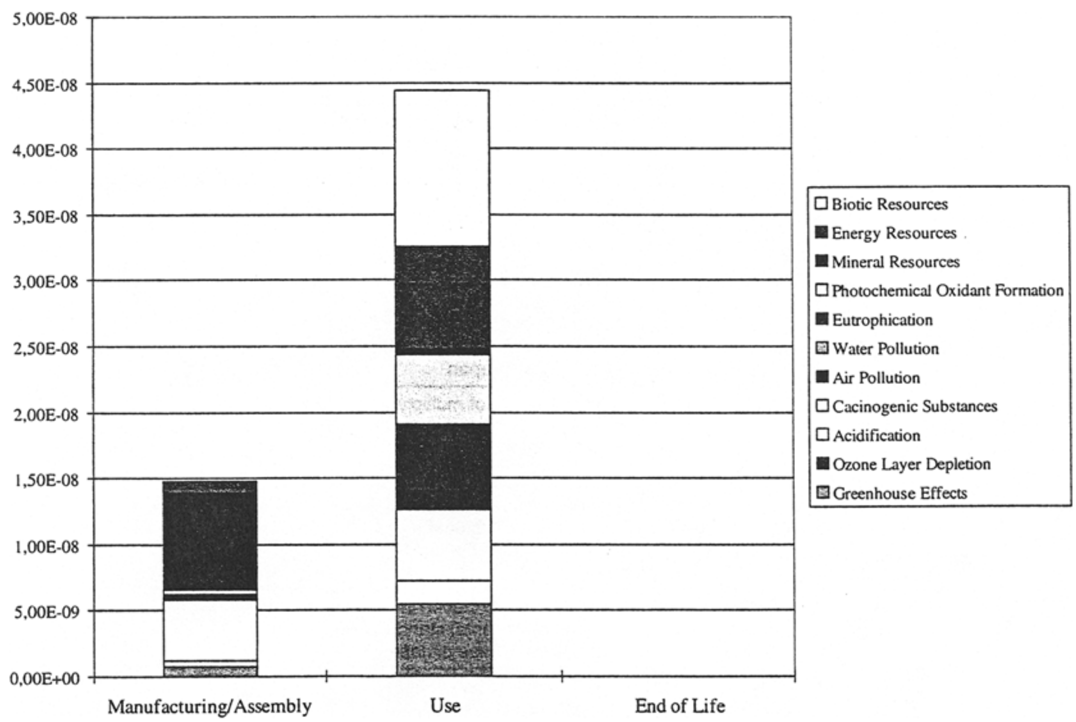

Fig. 4: The contribution of life cycle stages to the total life cycle impact of an imaginary copy machine

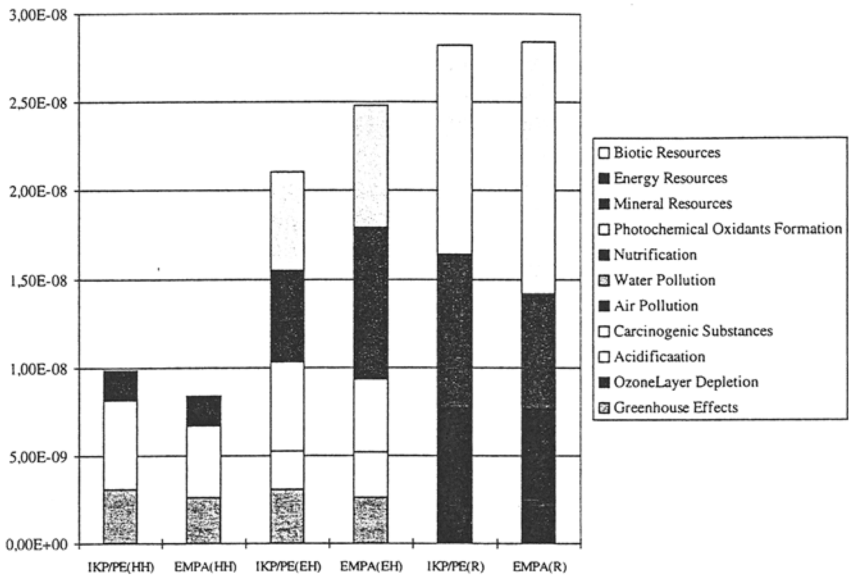

Fig. 5: The result of potential damage of safeguard subject of an imaginary copy machine with consideration of the effect of inventory data (IKP/PE, EMPA): HH; human health, EH; ecological health, R; resources

per. Paper is assumed to be made from wasted wooden products in the inventory. We treated the wood as one of the main biotic resources. This figure shows the case that the consumption of wood has been allocated fully to the production of paper. If we assume that the consumption of wood has not been allocated to the production of paper, the impact of biotic resources may be neglected. The results of weighting based on an inventory table (IKP/PE, EMPA) share certain similarities in the magnitude of safeguard subjects and the composition of impact categories.

Fig. 6 shows the contribution of environmental loading substances to the total impact and the difference of the results of weighting by the several inventory tables in this case study.

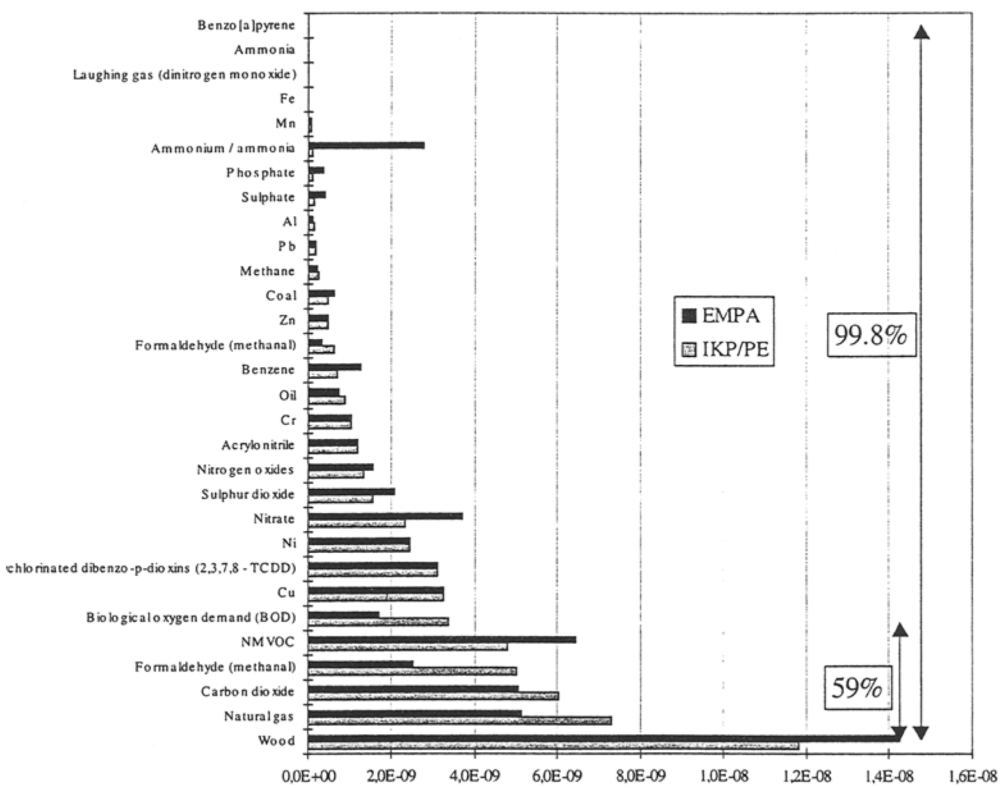

Fig. 6: The contribution of environmental loading substances for upper 30 substances to total life cycle impact of an imaginary copy machine. Larger 10 substances account for about 80 percent in total

This result can be obtained by the application of each inventory data to eq. (3). The serious 30 substances have been listed in this figure. In input-related substances, the consumption of wood, natural gas, copper, nickel, chromium, and crude oil are significant. In output-related substances, the emission of carbon dioxide, formaldehyde, non-methane hydrocarbon, biotic oxygen demand and polychlorinated dibenzo-p-dioxin (PCDD) are important. These larger five substances account for the 60 percentages and 30 substances account for almost 100% in total impact of an imaginary copy machine independent of the inventory data. In this study, we involved 68 substances totally for impact assessment. This means that we can cover almost the total impact of one product with the assessment for less than half of the numbers of substances.

From this figure, we can identify the significant substances for the following study. The difference of environmental impact by the emission of ammonia between the IKP/PE and EMPA is almost the same as the difference of impact by consumption of natural gas. However, the inventory of ammonia by EMPA is 25 times that of IKP in contrast with the inventory of natural gas by IKP which is only 1.4 times that of EMPA. This means that the sensitivity of total impact by various inventory data of the upper substances described in Fig. 6 is quite a bit higher than that of the other lower substances. It is important to consider carefully not only the substances that revealed a large gap of inventory data but also the substances that contribute to total environmental impact largely to improve the reliability.

According to these results, we arrive at our conclusion that the control of consumption of energy and paper in the use phase and that of rare metals in the manufacturing and reduction of the emission of carbon dioxide and toxic substances can contribute to reduce the total environmental impact effectively. As described in ISO 14040, LCA is an iterative approach. It is an appropriate strategy to introduce the result of impact assessment into the following investigation of LCI and interpretation to improve the reliability of the studies. Through these assessments, we can clarify what the important substances are, life cycle stage and the damage of safeguard subject, and apply these results into the next step as a screening result.

3 Conclusion

In this paper, we described the procedure of weighting methodology (I-O integration) instructive for screening LCIA with a case study. LCA practitioners can select from the following four types of results for decision making in accordance with their goals, inventory, category indicators, the damage of safeguard subjects, single index by the application of this methodology. These results are different in the numbers of quantified results and the degree of subjectivity. Aggregated single index obtained by this method is based on the simplified damage functions with linear approximation. This approach involves not only a normalization value and weighting factors of the impact category, but also the weighting across the safeguard subjects and the ratios of damaged area to reduce the overestimation for local impact categories.

Through the case study for an imaginary copy machine, we showed the effective approach to detect significant environment loading substances, impact categories that contribute the total environmental impact by dominant analysis, and revealed the possibilities to apply our method as Screening LCIA. These results enable us to focus on the main issues of products effectively and contribute to shorten the time for the following investigation in an iterative process.

This method has several limitations in methodological and operational aspects. Assessment by this method does not include exposure and fate analysis of emitted substances. The impact by the local pollution like odor and noise, and the effects of solid waste and radiation are excluded. Furthermore, this method is not available for another region of Japan, because the factors in this method are calculated with Japanese data. In Japan, several weighting methodologies have already been proposed. The characteristics of these methods such as concepts, calculation procedures, considering substances and impact categories are quite different. It is essential to consider them to perform an appropriate research. Several methods proposed in Japan have been described in Itsubo 2000. It is important to take considerations for these above points to improve the reliability and expand the applications.

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